PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : H01S 3/06, 3/094	A1	(11) International Publication Number:	WO 93/15536
		(43) International Publication Date:	5 August 1993 (05.08.93)

(21) International Application Number: PCT/US93/00887

(22) International Filing Date: 1 February 1993 (01.02.93)

(30) Priority data:
07/830,343 31 January 1992 (31.01.92) US

(71) Applicant: AMOCO CORPORATION [US/US]; Mail Code 1907A, Patents and Licensing Department, P.O. Box 87703, Chicago, IL 60680-0703 (US).

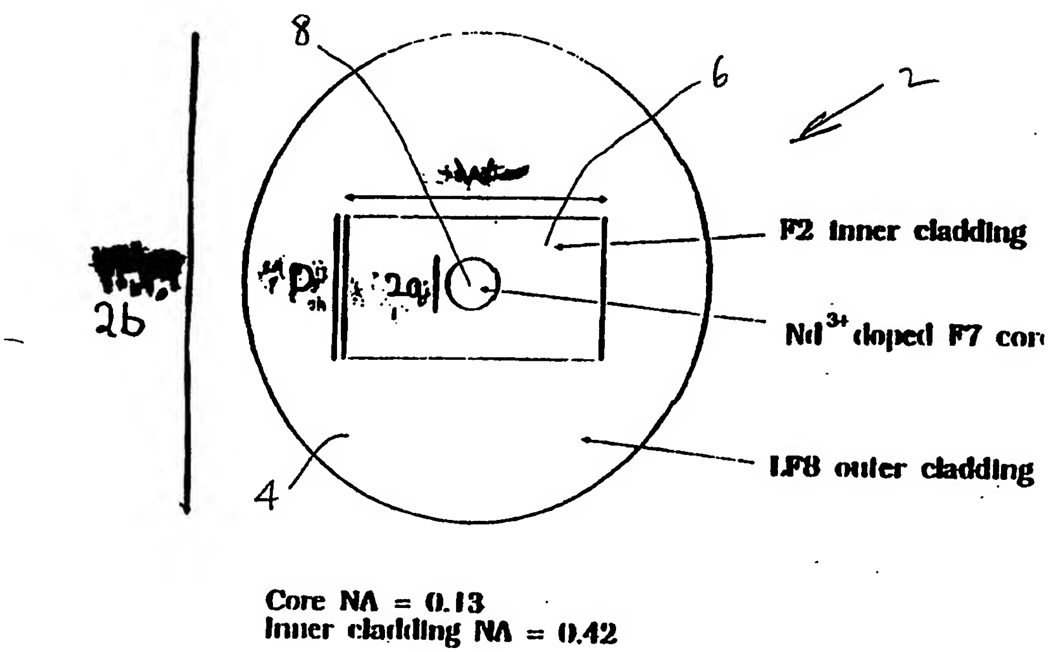
(72) Inventors: MINELLY, John, D. ; 21 Tremona Court, Tremona Road, Hampshire County, Southampton (GB). TAYLOR, Elizabeth, R. ; 8 Archery Grove, Woolston, Hampshire County, Southampton SO1 8EW (GB).

(74) Agents: LADD, Robert, G. et al.; Amoco Corporation, Patents and Licensing Department, Mail Code 1907, P.O. Box 87703, Chicago, IL 60680-0703 (US).

(81) Designated States: CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: LASER-DIODE PUMPED LASING FIBRE SCALABLE TO HIGH POWERS



(57) Abstract

A compound glass fibre fabricated from lead-silicate glasses that comprises an outer cladding, an inner cladding with a cross-sectional profile optimized for receiving multimode pumping radiation, and a single-mode central core within said inner cladding that is doped with a lasant material to maximize transfer of said multimode pumping radiation to said single mode doped core.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	FR	France	MR	Mauritania
AU	Australia	GA	Gabon	MW	Malawi
BB	Barbados	GB	United Kingdom	NL	Netherlands
BE	Belgium	GN	Guinea	NO	Norway
BF	Burkina Faso	GR	Greece	NZ	New Zealand
BG	Bulgaria	HU	Hungary	PL	Poland
BJ	Benin	IE	Ireland	PT	Portugal
BR	Brazil	IT	Italy	RO	Romania
CA	Canada	JP	Japan	RU	Russian Federation
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo			SE	Sweden
CH	Switzerland	KR	Republic of Korea	SK	Slovak Republic
CI	Côte d'Ivoire	KZ	Kazakhstan	SN	Senegal
CM	Cameroon	LI	Liechtenstein	SU	Soviet Union
CS	Czechoslovakia	LK	Sri Lanka	TD	Chad
CZ	Czech Republic	LU	Luxembourg	TG	Togo
DE	Germany	MC	Monaco	UA	Ukraine
DK	Denmark	MG	Madagascar	US	United States of America
ES	Spain	ML	Mali	VN	Viet Nam
FI	Finland	MN	Mongolia		

LASER - DIODE PUMPED LASING FIBRE SCALABLE TO HIGH POWERS.

Background of the Invention

The invention relates to fibre laser systems, and more particularly to fibre laser systems that have cores and claddings that are configured for high power applications.

Since the mid 1980's rare-earth doped fibre lasers and amplifiers nave been extensively researched worldwide. Lasers in fibre form provide low-cost, easily-produced devices at a number of wavelengths suitable for applications in telecommunications, sensing, medicine and spectroscopy. Fibre lasers offer a number of advantages over solid-state crystal lasers and bulk glass lasers. The waveguide nature of optical fibres means that very high power densities can be achieved in the core of a single-mode fibre at low power levels. The threshold powers of fibre lasers are therefore very low in comparison to bulk glass and crystal lasers. The high surface area to volume ratio of fibre lasers makes for easy heat dissipation that permits continuous wave (CW) operation of even three level systems such as erbium-doped fibres. In addition, the fibre lasers are broadly tunable and can provide high-power Q-switched output, modelocked pulses and narrow-linewidth operation using a number of now well established techniques. See, for instance, P. Urquart, "Review of rare-earth doped fire lasers and amplifiers", IEEE Proc. J., Vol. 135, pages 385 through 406.

Fibre lasers are normally considered to be low-power devices and not competitive with diode pumped Nd:YAG lasers. However, fibre lasers of current design are low-power devices that are not competitive with diode-pumped Nd:YAG lasers.

Summary of the Invention

The fibre laser according to the invention employs special-

glass technology, a novel inner-cladding fibre geometry and a number of aspects of fibre technology and micro-optics for end-fibre coupling and side coupling of the pump light from diode-arrays.

Description of the Drawings

Figure 1. Structure of the doubly-clad rare earth fibre for cladding pumping according to the invention.

Figures 2a through 2c. Three possible optical systems for diode-to-fibre coupling according to the invention.

Figures 3a through 3c. Fibre circuitry for scaling to high powers in the end pumping scheme according to the invention.

Figures 4a and 4b. Techniques for side injection into the active cladding pumping fibre according to the invention.

Figure 5. Output characteristics of Nd^{3+}-doped fibre pumped by a three watt array according to the invention.

Figure 6. Output characteristics of Er^{3+}/Yb^{3+}-doped fibre amplifier tandem pumped by the cladding pumped fibre laser according to the invention.

Description of the Invention

The technique of cladding has been shown to enable the pumping of fibres with single-mode rare-earth-doped cores by multimode diode array, thus allowing the fibre laser to exploit the increasingly-available, high-power diode pump sources. See, for instance, E. Snitzer et al.,"Double-clad, offset core Nd fiber laser", Proc. Conference on Optical Fibre Communications, New Orleans, 1988, PD5; H.Po et al., "doubly clad high brightness Nd fiber laser pumped by GaAlAs phased array", Proc. Conference on Optical fiber Communications, Houston, 1989, PD7; V.P.

Gapontsev et al., Proc. Conference on Advanced Solid-State Lasers, Hilton Head, 1991, WC1; and E. Snitzer et al., U.S.P.N. 4,815,079.

The basis of the technique is that the pump light is launched into a large, undoped, multimode fibre, core that readily accepts light from extended sources, whereupon it is absorbed active rare-earth ions located in an inner single-mode core within the multimode waveguide. Feedback of the fluorescence generated in and capture by the single-mode core results in lasing action with a guaranteed single-mode output.

Unfortunately, the linear geometry of diode-arrays and the resulting line-source mean that they are not ideal for coupling to conventional circular cross-section optical fibres. For example, an SDL three Watt diode array has emitting dimensions of 1 μm by 500 μm and the laser beam has divergence angles of 40 degrees and 10 degrees (FWHM) in the respective planes parallel and perpendicular to the diode junction. In the parallel plane, the full width at zero intensity is approximately 60 degrees. In the other plane, the intensity is almost uniform across the beam, so that the full width at zero intensity is again 10 degrees. For efficient coupling to an optical fibre, the image of the light source at the endface of the fibre should have a spacial extent less than the dimensions of the fibre core, and in addition, the divergence at the beam waist must not be significantly greater than the acceptance angle of the fibre. For this diode, the beam divergence in the fast diverging plane dictates that for 1:1 imaging in this plane, the fibre should have a numerical aperture (NA) in excess of 0.5 for 100 percent collection efficiency while the large array width dictates that the field should be compressed by a factor of approximately four to couple to a fibre of normal diameter (approximately 125 μm). Of course, the field compression in this plane result in an increase in the beam divergence by the same factor by which the field is compressed.

An ideal fibre for cladding pumping requires that ratio of inner cladding area to inner core area is minimized so as to keep the cavity losses to a minimum while at the same time enabling efficient coupling from the diode to the fibre. The ideal fibre is a rectangular structure with high NA having a major axis reduced with respect to the width of the diode array by the ratio, $\sin^{-1}(NA)/(\theta)$ where θ is the slower of the diode beam divergences and a minor axis large enough to contain a single mode core of conventional diameter, typically 8 μm.

The fibre employed in the preferred embodiment of the invention utilizes compound glass technology for the first time in a cladding-pumping scheme. The fibre is fabricated from Schott flint glass, (F2 and F7) and light flint glass (LF8) The approximate compositions of these glasses are given in Table 1.

Table 1

Compositions of Flint and Light Flint Glasses

Glass Type	SiO_2	Na_2O	K_2O	PbO
F : Flint	47	2	7	44
LF : Light Flint	53	5	8	34

Details of the fabrication of a neodymium doped fibre are shown schematically in Figure 1, wherein a cross-section of a fibre 2 according to the invention is illustrated. The fibre 2 was fabricated using a modified rod-in-tube technique. The fibre comprises a circular outer cladding 4, a rectangular inner cladding 6 and a neodymium-doped circular core 8 in the centre. This design gives the most efficient pump absorption for a given dopant concentration and area ratio. See, for instance, H. Po et al., above. Schott flint glasses LF8, F2 and F7 were used for the outer cladding 4, the inner cladding 6 and the core 8, respectively.

The core 8 was prepared from a mixture of three weight-percent Nd_2O_3 in F7 glass melted in a platinum crucible at approximately 1200 degrees Celsius. A cane of core glass of approximately three to five mm in diameter is drilled out of the prepared F7 glass and inserted into a "tight fit" tube of F2 glass having an outer diameter of approximately 10 mm. A tube of F7 glass with an inner diameter corresponding to that of the F2/F7 core rod was milled down on opposite sides to form the rectangular cladding. The outer cladding of LF8 glass was made out of two D-shaped section and a circular outer tube. In all, six separate pieces made up the preform. The pieces were milled on an ultrasonic rotary machine equipped with diamond impregnated tools. All pieces were acid etched with HF/H_2SO_4 prior to assembly. This ensures low losses at the different interfaces. The fibre was drawn conventionally in a low temperature furnace at around 600 degrees Celsius.

The dimensions of the inner cladding 6 are typically 120 μm by 20 μm, the inner core 8 diameter is typically 5.5 μm and the outer cladding 4 diameter is typically 150 μm. The NA between the outer cladding 4 and inner cladding 6 (LF8/F2) is 0.42 and the Nd-doped F7 core 8 NA is 0.13. The inner cladding 6 is designed to match as closely as possible to the large diffraction angle of the diode, and whilst minimizing the area of the rectangular guide, thus optimizing the pump absorption in the core and the laser threshold. The background loss at the lasing wavelength of 1057 nm is 0.9 dB/m (the intrinsic loss of the undoped F7 core 8 clad with F2), and the inner cladding 6 attenuation at the pump wavelength of 808 nm is 0.3 dB/m. These values are comparable to the losses in bulk glasses, indicating that the fabrication process does not introduce significant additional loss. The absorption of pump light propagating in the inner cladding by the doped single -mode core 8 is approximately 15 dB/m.

The fibre 2 described above is considered superior to earlier cladding-pump designs because a high numerical aperture

is achieved in all-glass design. Previous cladding-pumping schemes have either employed soft polymer outer claddings, such as described by H. Po et al., above, or compromised on NA, such as described by E.Snitzer et al. and V.P. Gapontsev et al., above. The soft polymer coating/outer cladding, while enabling NA's of up to 0.4 in silica fibres, introduces problems in cleaving fibers of irregular cross-section, since the coating must be removed prior to cleaving. Such fibres are those of rectangular design, and in direct coating of the endface with the necessary dichroic reflectors that allow high pump transmission and high reflection of the intracavity laser light, since the presence of the polymer often causes contamination of the coating apparatus. The lower inner cladding NA of silica based all-glass fibres limit the launch efficiency from laser diodes. An additional advantage of the choice of glasses described above is that they give higher radiative cross-sections and the possibility for higher doping levels without concentration quenching. These fibres offer higher gain than similarly doped silica fibres, thus enabling the construction of devices such as Q-switched fibre lasers that require high gain for efficient operation.

There are several methods by which light can be coupled from a diode array into the rectangular inner cladding 6 of the fibre 2. In general, the requirement will be for 1:1 imaging, or perhaps a small amount of expansion to slightly reduce the launch NA in the fast diverging plane and for field compression and corresponding increase in NA in the other plane. These requirements arise from the need to maximize the coupling into an optimized fibre. Three coupling methods are shown in Figures 2a through 2c.

The first method, shown in Figure 2a, uses two crossed cylindrical lenses 10 for collimation of pumping radiation from a diode array 12, and a single spherical lens 14 for refocussing onto the fibre 2. The ratio of the focal lengths of the two cylindrical lenses 10 is equal to the required field compression

ratio. For miniaturization, the cylindrical lenses 10 may comprise special D-shaped fibres, and the spherical lens 14 may be a fibre coupling sphere or ball lens. These are miniature spherical lenses with focal lengths between several hundred microns and a few millimetres. when these spheres are glued to a fibre end, they can act as collimators, for example, in expanded beam connectors. Miniaturized coupling systems using shorter focal lengths enable compact coupling systems, and also reduce aberrations.

The second method, shown in Figure 2(b), is similar to the one described above in connection with Figure 2(a), but it uses and anamorphic prism pair 16 to expand the collimated beam in the transverse plane, and two spherical lenses 18 for collimation and focusing.

While compact coupling systems can be achieved with careful design of lenses and precise alignment , it is simpler to butt the fibre 2 directly to the facet of the diode array 12. The necessary field compression in this case is achieved by the use of a special waveguide 20 tapered in one plane only as shown in Figure 2(c). The taper can be fabricated by etching differentially along the length of the fibre 2 or by locally grinding the fibre 2 in the appropriate direction. See, for instance, C.D. Hussey et al., "Optical Fibre polishing with a motor driven polishing wheel", Electronics Letters, 1988, Vol. 24, pages 805 through 807. At the input, the light form the diode array 12 excites low order modes in the transverse plane, since the divergence angle in this plane is significantly less than the acceptance angle of the fibre 2. The light remains guided so long as the compression ratio does not exceed the limit imposed by the NA of the fibre.

If pump light is launched from two diode arrays into two undoped rectangular fibres of dimensions D*W, it is possible to couple the total power into a fibre of dimension 2D*W by the technique shown in Figures 3(a) through 3(c). First, two

individual fibres 22 are polished or ground parallel to their major axis until the rectangular waveguides are exposed to the air, as shown in Figure 3(b). They are brought together in the manner of a multimode polished coupler, and cut and polished across the point of contact, as shown in Figure 3(c). The fibre of depth 2D that may contain the doped single-mode core 8 is then butted directly to the composite fibre 2. Rather than polishing circular fibres to obtain a localized D-Fibre, a special D-fibre can be fabricated for the purpose, as can a fibre 2 with a cladding glass that can be preferentially etched. this technique can be extended by concatenation as shown in Figure 3(a) to combine the pump from multiple diode arrays or from the subarrays 22 of diode bars.

Another way that cladding-pumped fibre-lasers can be scaled to high powers is by injecting pump light transversely at multiple entry points in the fibre. The entry points must be separated by sufficient length of cladding-pumping fibre that a high proportion of the pump light injected by the previous pump source has been absorbed to ensure that significant residual light is not coupled out of the fibre at the entry point. The technique can be an efficient scaling technique for four-level lasers, provided that the number of entry points is not too great, and that the fibre loss is low. Eventually, a limit is reached where the proportion of extra gain available due to further pump light is offset by the additional cavity loss in the extra length of fibre. In a three-level system, the additional cavity length increases the threshold power proportionally, making the scheme less attractive.

The technique for side injection is illustrated schematically in Figure 4. The cladding pumping fibre 2 is polished in the plane orthogonal to the long axis so that the inner cladding 6 is exposed on one side over a short length. This plane is chosen because the fibre 2 has "spare numerical aperture" over the diode array 12 in the long axis. Attempting to side inject in the other plane results in high radiation loss.

The optical axis of the light delivery system from the diode array 12 is slightly tilted with respect to the axis of the receiving fibre. The delivery system can be by any of the means described above. The actual coupling mechanism may be by focusing with a spherical lens 26 through an index-matched glass block 28 or via a fibre 2 polished at a shallow angle. Alternatively, standard multimode-couplers may be used for injection. These are standard passive fibre optic components manufactured either by fusing and tapering two multimode fibres until overlap of the modal fields induces coupling, or by polishing each fibre in turn until the cores are exposed, and placing them sid by side again to induce coupling. However, if many modes in the input fibre are excited, then the maximum power coupling to the second prot is fifty percent, because although each individual mode may be fully coupled, the coupling length for each mode is different. Averaging the coupled power over all the modes yields a 50:50 split at the output. For purposes of side injecting pump light to cladding-pumping fibres, this technique, though feasible, is less attractive than the means described above, since the number of entry points increases as a result of the fifty percent coupling restriction that can be coupled at each section.

The output characteristics of the fibre laser according to the invention, pumped by a three Watt SDL GaAlAs multi-stripe diode array are shown by line 30, representing output power as a function of diode pumping power. With the pump diode operating at full power, the fibre laser achieves 1.07 Watt output power at a peak wavelength of 1.057 μm. The overall efficiency with respect to diode power is around fifty percent, which is close to the maximum attainable.

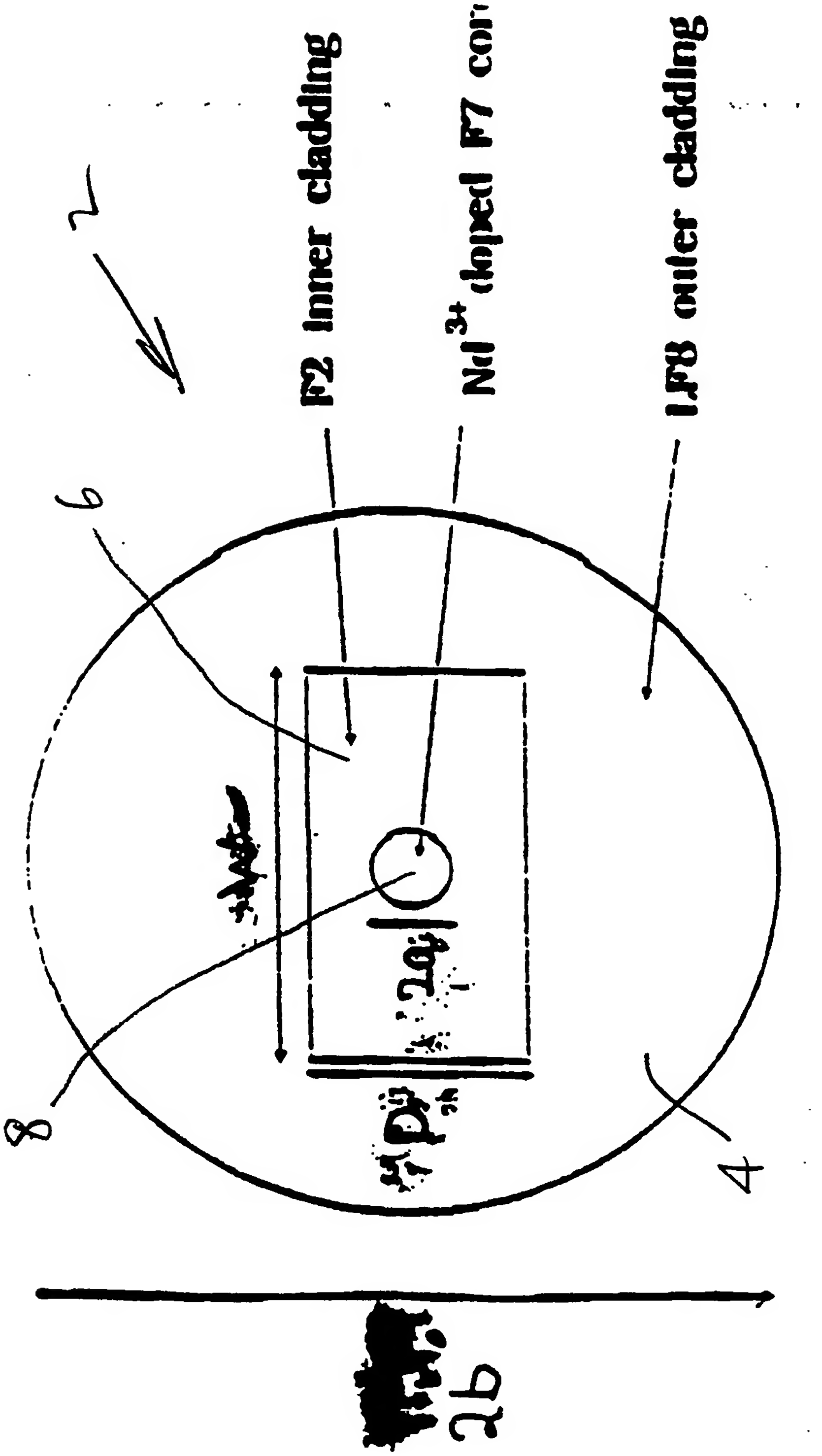
To demonstrate a possible application of the cladding pumped fibre laser, it was employed as a pump source for a Er^{3+}/Yb^{3+}optical fibre amplifier. An amplifier gain of 45 dB and output signal powers in excess of +20 dBm have been demonstrated. the amplifier characteristics are illustrated in Figure 6,

wherein line 32 represents gain as a function of input signal power, and line 34 represents output power as a function of input power.

Thus there has been described an improved optical fibre suitable for lasing at high powers. It will be understood that various changes in the details, materials, steps and arrangements of parts that have been described and illustrated above in order to explain the nature of the invention may be made by those of ordinary skill in the art within the principle and scope of the invention as expressed in the appended claims.

What is claimed is:

1. A compound glass fibre fabricated from lead-silicate glasses that comprises an outer cladding, an inner cladding with a cross-sectional profile optimized for receiving multimode pumping radiation, and a single-mode central core within said inner cladding that is doped with a lasant material to maximize transfer of said multimode pumping radiation to said single mode doped core.



Core NA = 0.13
Inner cladding NA = 0.42

Figure 1

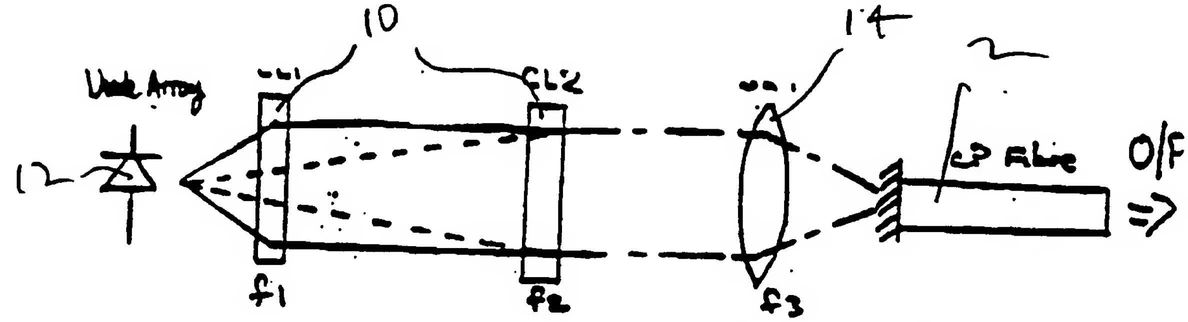


Fig 2(a)

$f_2 = 4f_1$ (for 4 x compression
$f_3 = f_1$

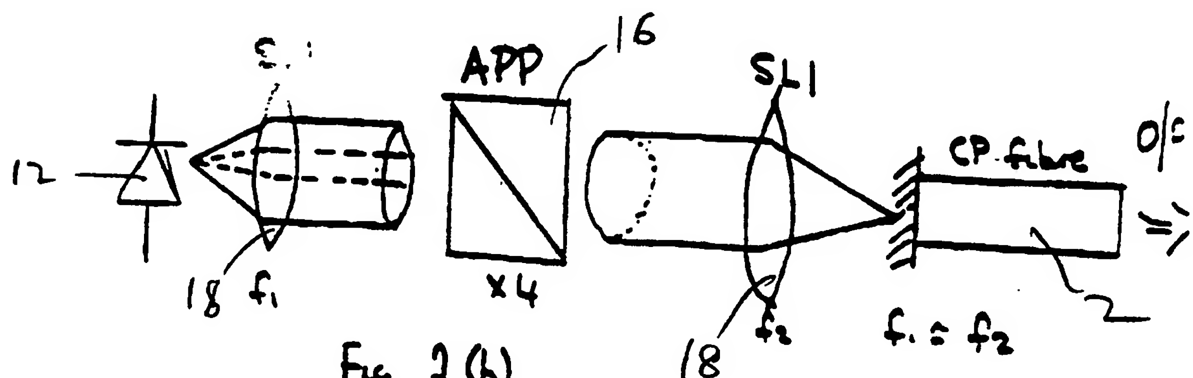


Fig 2(b)

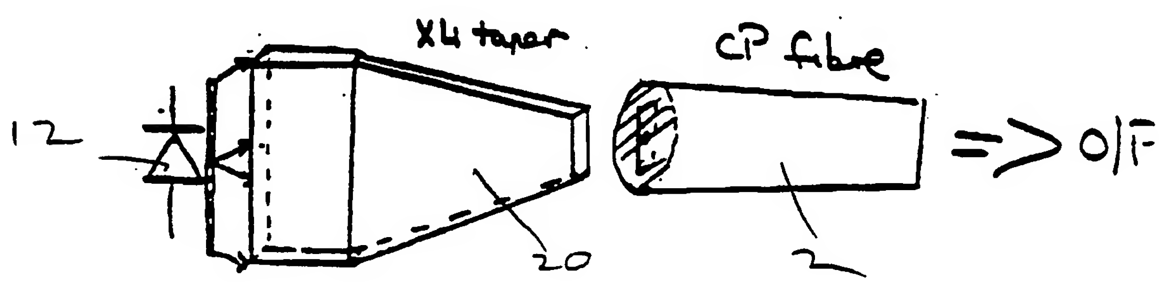


Fig 2(C)

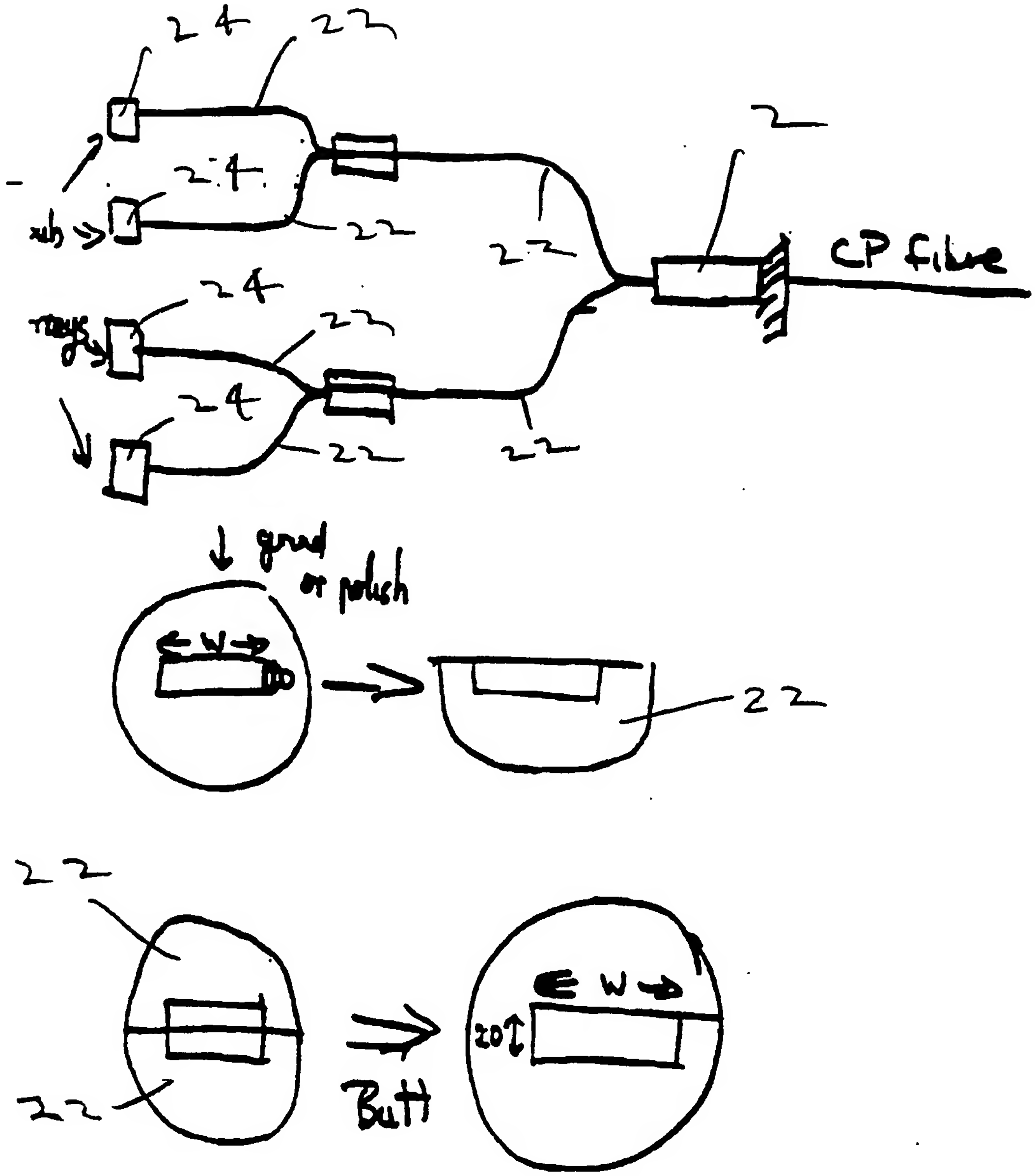

24
22
24
22
2
22
CP fibre
24
22
24
22
22
grind or polish
W
22
22
W
20
22
Butt

Figure 3

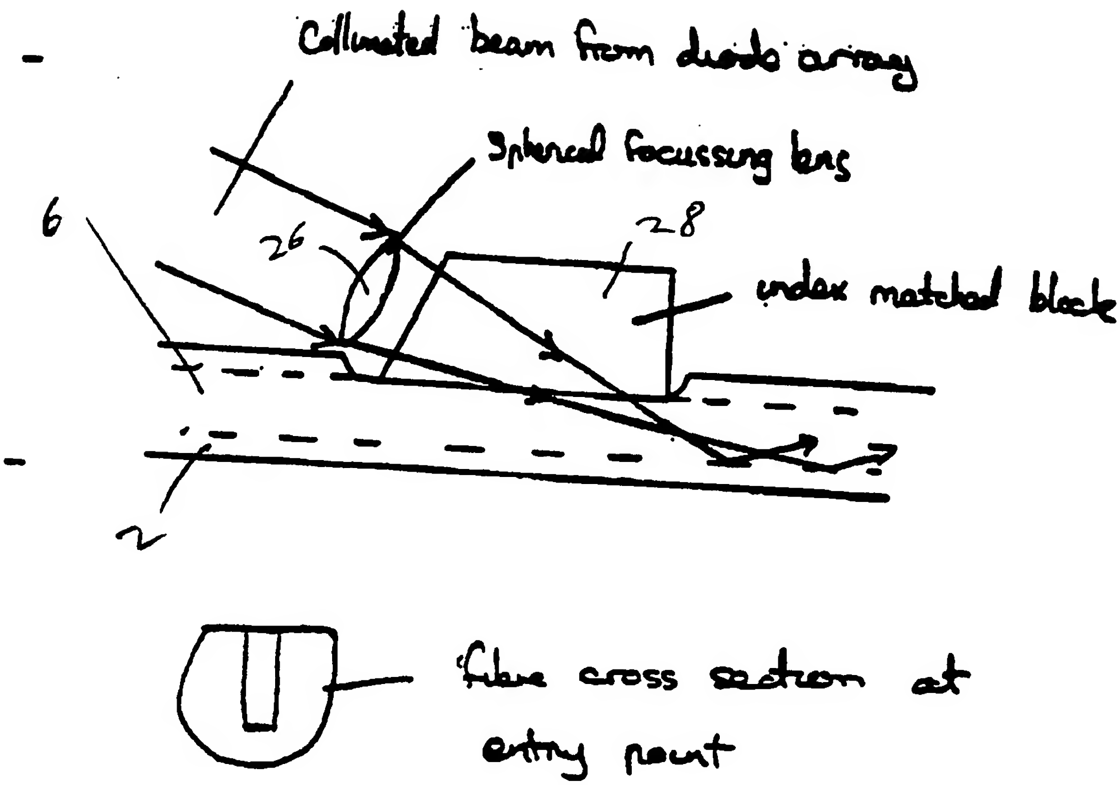

Collimated beam from diode array
Spherical focussing lens
6
26
28
index matched block
2
fibre cross section at entry point

Fig (4,)

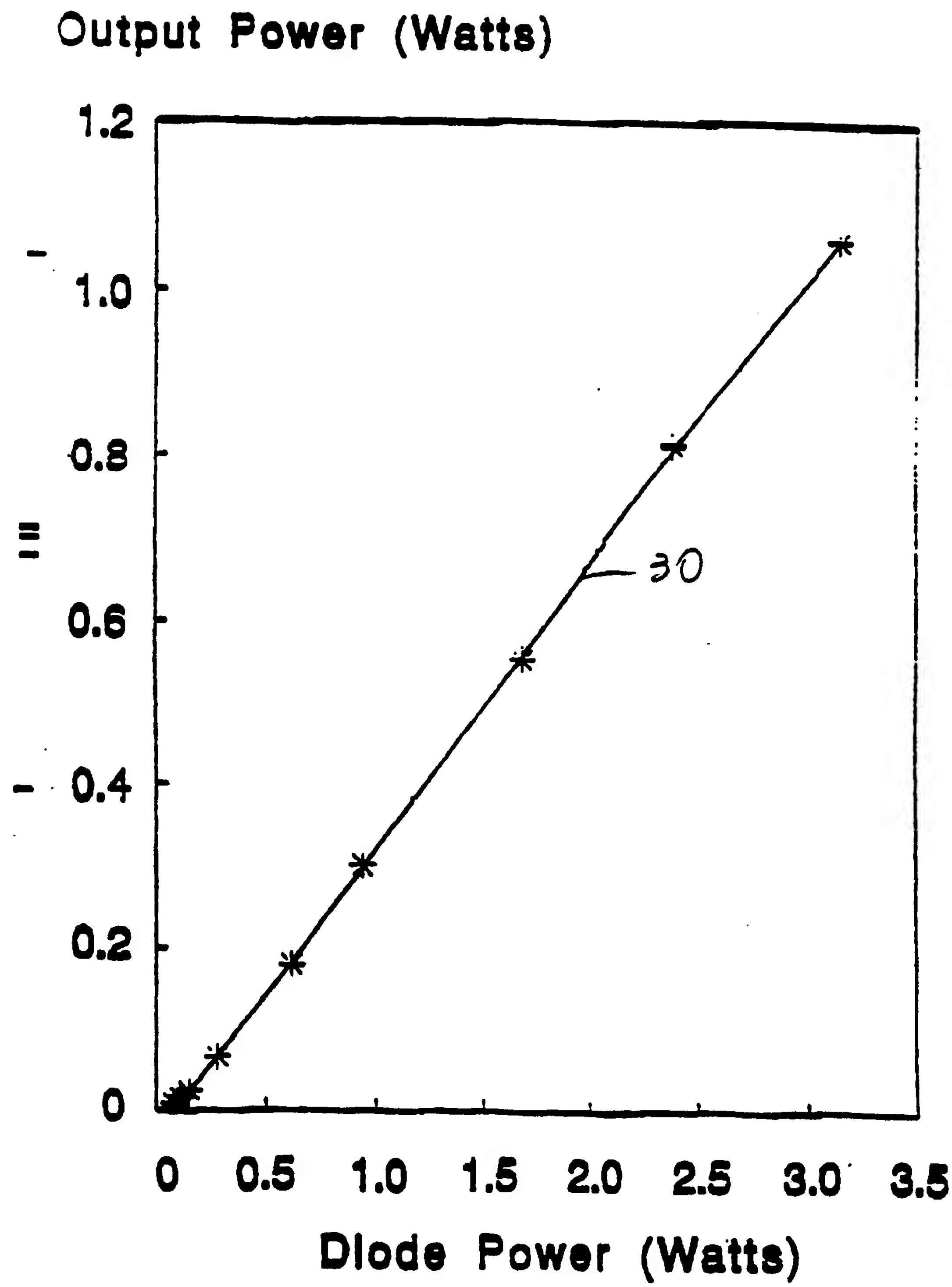

Output Power (Watts)
1.2
1.0
0.8
0.6
0.4
0.2
0
30
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Diode Power (Watts)

FIG 5

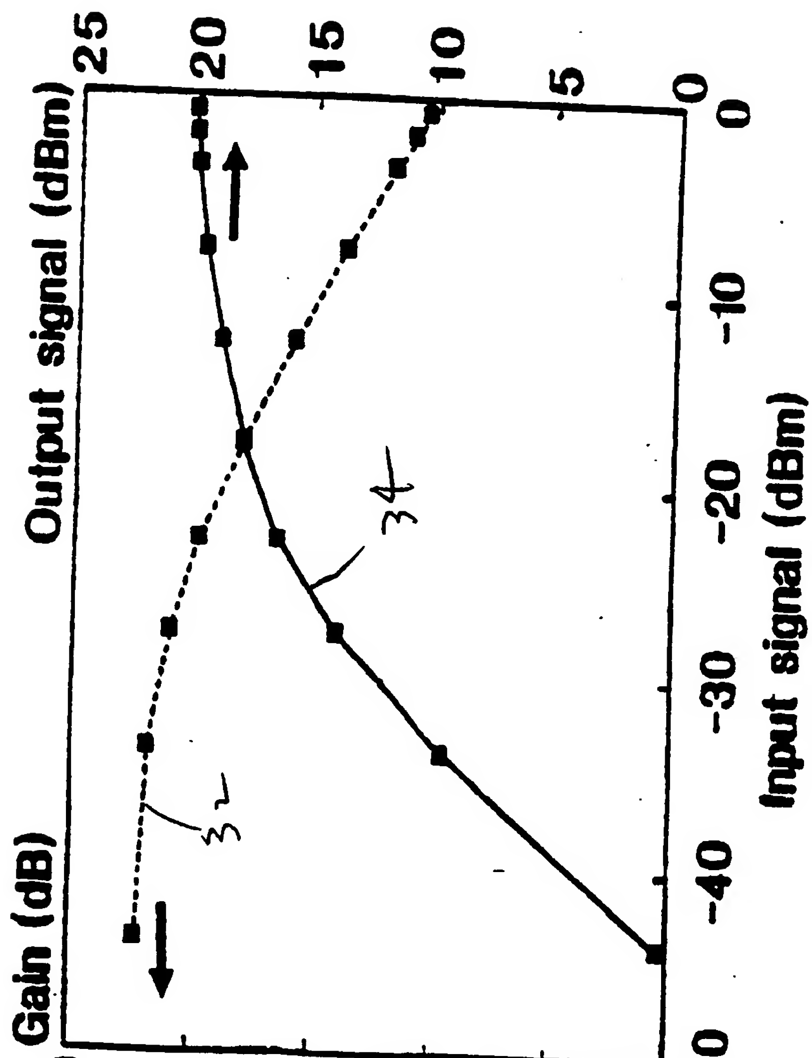

Gain (dB)
Output signal (dBm)
Input signal (dBm)
32
34
50
40
30
20
10
0
25
20
15
10
5
0
-50
-40
-30
-20
-10
0

Figure 6

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 93/00887

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 H01S3/06; H01S3/094

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H01S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category°	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	US,A,3 808 549 (R.D. MAURER) 30 April 1974 see column 2, line 49 - line 59; figure 1 see column 3, line 21 - line 32 see column 3, line 65 - column 4, line 59 ---	1
A	US,A,4 829 529 (J.D. KAFKA) 9 May 1989 see column 2, line 5 - line 27; figures see column 2, line 54 - line 57 ---	1

-/--

° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

3

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
08 JUNE 1993	18 JUN 1993
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	BATTIPEDE F.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	MATERIAL RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS vol. 172, 1989, PITTSBURG, PA, US pages 321 - 327 E.R. TAYLOR ET AL. 'Application-specific optical fibres manufactured from multicomponent glasses' see page 321, paragraph 3 - page 322, paragraph 1 see page 326, paragraph 4 ---	1
A	EP,A,0 320 990 (POLAROID) 21 June 1989 cited in the application see column 1, line 9 - line 13 see column 3, line 25 - column 4, line 7 see column 5, line 16 - line 45 see figures 1,2 -----	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

US 9300887
SA 70076

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information. 08/06/93

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-3808549	30-04-74	None	
US-A-4829529	09-05-89	None	
EP-A-0320990	21-06-89	US-A- 4815079 DE-A- 3874701 JP-A- 1260405	21-03-89 22-10-92 17-10-89